(30)

Ap. J.

54/577

YELLOW HYPERGIANTS AS DYNAMICALLY UNSTABLE POST-RED-SUPERGIANT STARS

Richard B. Stothers and Chao-wen Chin

Institute for Space Studies, NASA/Goddard Space Flight Center,

2880 Broadway, New York, NY 10025

ABSTRACT

According to recent theoretical studies, the majority of single stars more massive than 30 $M_\odot$ successfully evolve into red supergiants, but then lose most of their hydrogen envelopes and metamorphose into hot blue remnants. While they are cool, they become dynamically unstable as a result of high radiation pressure and partial ionization of the gases in their outer layers. It is shown here that these unstable red-supergiant models repeatedly shrink and re-expand on a thermal time scale when perturbed by heavy bursts of mass loss. Consequently, they fill up the domain of yellow hypergiants on the Hertzsprung-Russell diagram and display very fast rates of evolution there, as observed.

Subject headings: stars: evolution-- stars: mass loss-- stars: oscillations-- stars: variables: other

1. INTRODUCTION

Yellow hypergiants form a class of very luminous yellow supergiants that show strongly turbulent photospheres and high rates of mass loss (de Jager 1998). With effective temperatures of only 4000-7000 K, they occupy the cooler half of the Hertzsprung Gap, which is the wide yellow band that separates red supergiants from luminous blue variables (LBVs or S Doradus variables) on the Hertzsprung-Russell (H-R) diagram. The hotter half, 7000 - 10,000 K, is a nearly empty sector, referred to by Jager & Nieuwenhuijzen (1997) as the Yellow Void.

It is now believed that yellow hypergiants are the cores of massive stars that have recently evolved out of a much cooler red-supergiant state (e.g., Stothers 1975; Schaller et al. 1992, Bresssan et al. 1993; Meynet et al. 1994; Stothers & Chin 1996). Ordinary yellow supergiants showing normal masses and normal photospheric spectral lines, however, are probably stars that are rapidly evolving away from the main sequence (de Jager 1998). The rarity of both groups of yellow supergiants can be attributed to the fast rates of contraction and expansion of stars across the Hertzsprung Gap.

In recent years, a large amount of quantitative empirical information has become available on the rates of apparent evolution for several of the yellow hypergiants (see the review by de Jager [1998] and below). We present here a detailed comparison of these rates with new theoretical predictions based on revised stellar models. It turns out that the yellow hypergiants probably do not represent a series of steps along a final track into a permanent blue end-state, but, rather, they may define a set of short blue loops repeatedly emerging out of the red-supergiant region as a result of dynamical instability in the outer layers. This may explain why there are so many yellow hypergiants as compared to luminous red supergiants.

After a brief description of the evolutionary setting of these stars on the H-R diagram (§ 2), we discuss the combined-- secular and dynamical-- behavior of the stellar models, along with a detailed comparison with observations (§ 3). Our main conclusions (§ 4) follow.

2. H-R DIAGRAM

The brightest identified supergiants in the Galaxy, in M33, and in the Large Magellanic Cloud are plotted on the H-R diagram in Figure 1. The observational data come primarily from de Jager's (1998) and van Genderen's (2001) compilations, with supplementary data taken from van Genderen (1992), Israelian, Lobel, & Schmidt (1999), and Nieuwenhuijzen & de Jager (2000). Stars recognized definitely to be yellow hypergiants have their ranges of variability indicated by dashed lines in the figure.

Shown also in the figure are the theoretical boundaries of a zone that encloses our dynamically unstable post-red-supergiant models taken from two earlier papers (Stothers & Chin 1996, 1999). To recapitulate briefly the properties of these models, the outer envelope is dynamically unstable as a result of two factors: (1) high radiation pressure due to the reduced stellar mass and (2) enlarged partial ionization zones of hydrogen and helium due to the low effective temperature in red and yellow supergiants. Although the models are dynamically unstable, we assume that the instability leads only to enhanced mass loss, with no direct effect on the underlying evolution. Observations confirm such enhanced rates of mass loss (de Jager 1998), which are not normally large enough to invalidate our basic model assumption about quasi-static evolution on a non-dynamical time scale (here time scales longer than ~1 yr).

We have recalculated the hot edge of the instability strip on the H-R diagram by using the rigorous criterion for dynamical instability based on a solution of the radial wave equation for small adiabatic perturbations rather than the approximate criterion $<\Gamma_1> = 4/3$ used earlier. Our results turn out the depend slightly on the treatment of convection, which is strongly nonadiabatic in the mostly radiative outer envelope. The treatment adopted is Böhm-Vitense's mixing-length theory with a constant ratio of convective mixing length to local pressure scale height, α_P, where the total pressure includes radiation pressure but not turbulent pressure. Figure 1 shows the hot edge for three typical values of α_P. Notice that models with smaller α_P are dynamically more unstable. The reason for this is that, if α_P is small, convection becomes less efficient; the temperature gradient then steepens relative to the pressure gradient. As a result, radiation pressure becomes a larger fraction of the total pressure, and this rise in radiation pressure reduces the dynamical stability of the envelope.

All of the observed *yellow hypergiants* fall cleanly into the theoretically predicted box. We infer, therefore, that the other yellow supergiants found inside this box are either unrecognized hypergiants or else are crossing the Hertzsprung Gap for the first time. There exists strong chemical and surface gravity evidence that the brightest of the yellow supergiants, HD 33579, has not yet been to the red region (Humphreys, Kudritzki, & Groth 1991; Nieuwenhuijzen & de Jager 2000).

The observational problem presented by the Yellow Void (7,000-10,000 K), where no stable star except HD 33579 is found, has no simple theoretical solution in terms of a sudden acceleration of the star's secular Helmholtz-Kelvin contraction or expansion there (Stothers & Chin 1996). Although de Jager & Nieuwenhuijzen (1997) have associated the existence of this nearly empty zone with the gravitationally unbound nature of the atmospheres of the Yellow Void stars (Nieuwenhuijzen & de Jager 1995), our new evolutionary models, described below, offer an alternative explanation. First, we note that the Void actually extends between 7000 K and the cool edge of the LBV strip, which rises diagonally from 10,000 K at the bottom of the Void to 20,000 K at its top (Fig. 1). If massive stars, when they have become red supergiants, execute short blue loops caused by violent outbursts of mass loss, they will fill up the region between 4000 K and 7000 K. On their final blueward swing, they will cross the Void and end up on the hot side of the Hertzsprung Gap, among the LBVs. This interpretation would suggest that many of the ordinary-looking yellow supergiants scattered within the hypergiant region are actually unrecognized hypergiants on transient blue loops, and are not stars on their first evolutionary crossing of the Hertzsprung Gap.

3. DYNAMICALLY TRIGGERED BLUE LOOPS

It is known from observations that yellow hypergiants approach the Void from the right and then "bounce" back to the red (de Jager & Nieuwenhuijzen 1997). This bouncing phenomenon takes place on two different time scales. The longer time scale of several decades can be picked out easily from published photometry for ρ Cas (Beardsley 1961; Zsoldos & Percy 1991; Percy, Kolin, & Henry 2000), IRC +10420 (Gottlieb & Liller 1978; Jones et al. 1993), and HR 8752 (Zsoldos 1986; Percy & Zsoldos 1992).

Theory actually predicts this phenomenon. In Figure 2, we show a transient blue loop that has been abruptly triggered by sudden, heavy mass loss from a secularly and dynamically unstable red supergiant model of initially 60 $M_{\odot}$. This model occurs along an evolutionary track based on otherwise standard rates of mass loss (Stothers & Chin 1999). What is new here is that we have perturbed the model by abruptly raising the mass-loss rate to 10^{-2} $M_{\odot}$ yr^{-1} when T_e < 5000 K. The exact mass-loss rate and the exact threshold effective temperature, however, turn out to be unimportant so long as the model suddenly begins moving to the blue.

The minimum mass-loss rate needed, however, is close to 10^{-2} $M_\odot$ yr^{-1}.

The outgoing trajectory of the blue loop covers almost exactly the same ranges of effective temperature in 20 yr (6000-7000 K) and in 50 yr (5000-7000 K) that IRC +10420 and ρ Cas, respectively, are known to have covered in the same intervals (de Jager & Nieuwenhuijzen 1997). Variable A in M33 seems to have moved just as quickly (Humphreys, Jones, & Gehrz 1987). The nearly invariant speed of these observed trajectories is matched closely by the theoretical models, regardless of where in the red region, or even in the yellow region, the blue loop is initiated. Only the length of the blue loop varies, a bluer tip being associated with a stronger initial mass-loss perturbation. The blue loop shown, however, is very characteristic.

Observations reveal also the existence of a shorter time scale for bouncing against the Yellow Void, represented by the known excursions of HR 8752 between 4000 K and 8000 K in a time span of less than 10 yr (de Jager & Nieuwenhuijzen 1997). These oscillations may signal a response to more frequent, but less extreme, episodes of mass loss. In our models, the outer envelope of a star like HR 8752 is both dynamically and secularly unstable. Even its atmosphere is unstable (de Jager 1998). Therefore, the likelihood exists that superimposed on the slower secular blue loops are faster blue loops occurring on a nearly dynamical time scale. These may be limited by the atmospheric instability (de Jager et al. 2001). To test this idea, a quasi-evolutionary sequence of fully hydrodynamical models would be needed, including accurate treatments of the atmosphere and of the obscuring gas ejecta. We have not computed such models.

4. CONCLUSION

The theory of ionization-induced dynamical instability (Stothers & Chin 1996) that we have adapted to yellow hypergiants is able to explain the observed secular time scales, locations, and frequency of these stars in the H-R diagram in an approximate, but self-consistent way. Although our theory cannot yet predict the rate of dynamical mass loss owing to a lack of sufficiently sophisticated hydrodynamical models, the same can be said for the rate of stellar wind mass loss for stars of any kind.

Observationally, yellow hypergiants display a strong resemblance to classical LBVs (de Jager & van Genderen 1989; Nieuwenhuijzen & de Jager 2000; van Genderen 2001). The similarity of their characteristics is confirmed in our theory as being more than merely superficial, and reflects consecutive, though distinct, phases of dynamical instability. A problem remains, however. In evolving from a yellow hypergiant to a classical LBV, a massive star must eventually cross the Yellow Void on the H-R diagram. Does such a star accomplish this wholly dynamically or is there also a slower secular component?

ACKNOWLEDGMENTS

It is a pleasure to acknowledge many helpful communications from C. de Jager and A. van Genderen. Overall support for our work was provided in part by the NASA Climate Research Program.

REFERENCES

Beardsley, W.R. 1961, ApJS, 5, 381

Bressan, A., Fagotto, F., Bertelli, G., & Chiosi, C. 1993, A&AS, 100, 647

de Jager, C. 1998, A&A Rev., 8, 145

de Jager, C., Lobel, A., Nieuwenhuijzen, H., & Stothers, R. 2001, MNRAS, submitted

de Jager, C., Nieuwenhuijzen, H. 1997, MNRAS, 290, L50

de Jager, C., van Genderen, A.M. 1989, in Physics of Luminous Blue Variables, ed. K. Davidson, A.F.J. Moffat., H.J.G.L.M. Lamers (Dordrecht: Kluwer), 127

Gottlieb, E.W., Liller, W. 1978, ApJ, 225, 488

Humphreys, R.M., Jones, T.J., Gehrz, R.D. 1987, AJ, 94, 315

Humphreys, R.M., Kudritzki, R.P., Groth, H.G. 1991, A&A, 245, 593

Israelian, G., Lobel, A., Schmidt, M.R. 1999, ApJ, 523, L145

Jones, T.J., et al. 1993, ApJ, 411, 323

Meynet, G., Maeder, A., Schaller, G., Schaerer, D., & Charbonnel, C. 1994, A&AS, 103, 97

Nieuwenhuijzen, H., de Jager, C. 1995, A&A, 302, 811

----------------. 2000, A&A, 353, 163

Percy, J.R., Kolin ,D.L., Henry, G.W. 2000, PASP, 112, 363

Percy, J.R., Zsoldos, E. 1992, A&A, 263, 123

Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269

Stothers, R.B. 1975, ApJ, 197, L25

Stothers, R.B., & Chin, C.-w. 1996, ApJ, 468, 842

-----------------. 1999, ApJ, 522, 960

van Genderen, A.M. 1992, A&A, 257, 177

-----------------. 2001, A&A, 366, 508

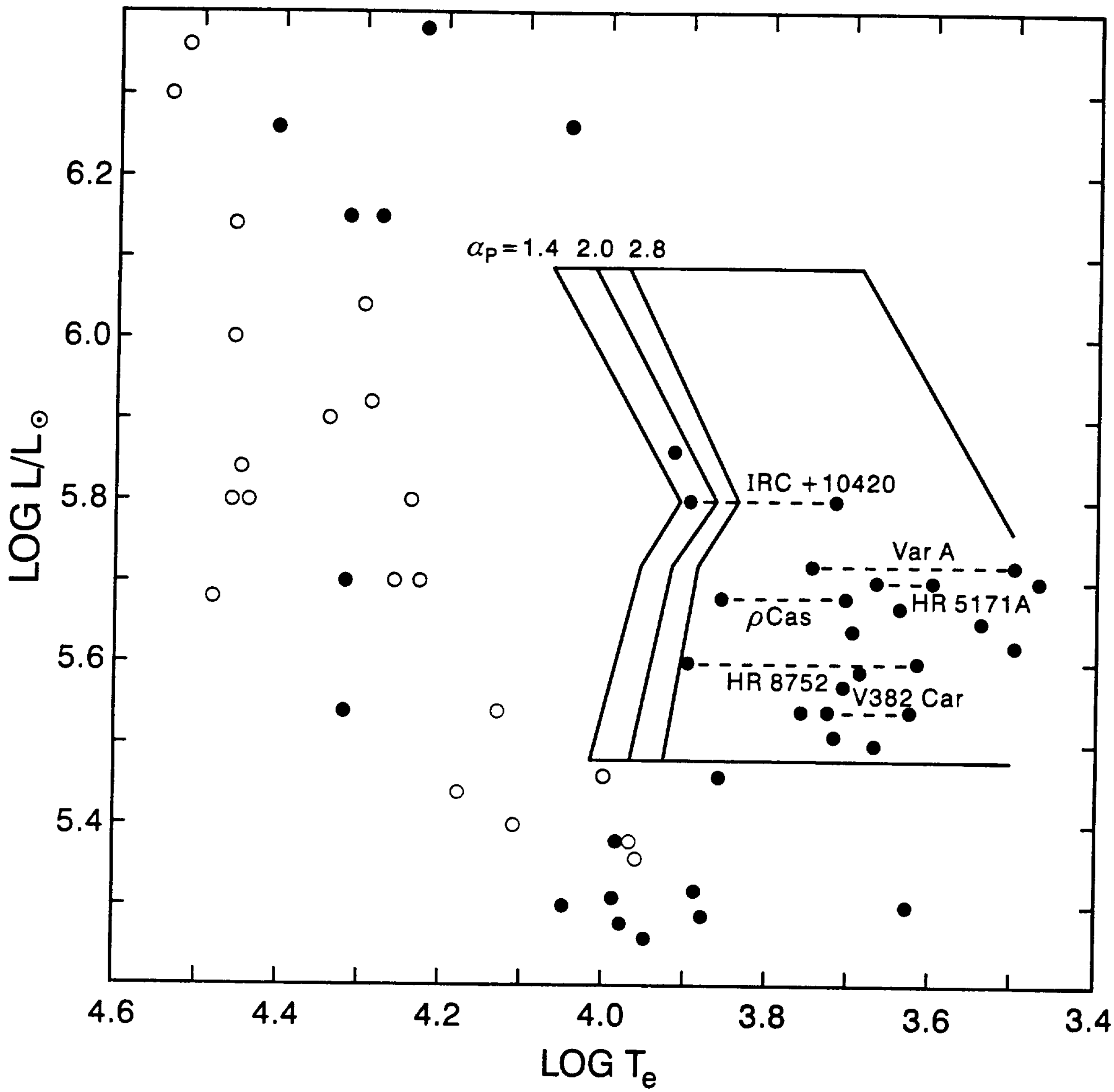
Zsoldos, E. 1986, Observatory, 106, 156

Zsoldos, E., Percy, J.R. 1991, A&A, 246, 441

FIGURE CAPTIONS

Fig. 1.-- H-R diagram showing the positions of the brightest known supergiants in the Galaxy, in M33, and in the Large Magellanic Cloud. Identified yellow hypergiants are plotted with their known ranges of variability indicated by dashed lines. Circles indicate known and suspected LBVs. The theoretically predicted hot border of yellow hypergiants is plotted for three values of the convective mixing-length parameter, as are also the predicted upper and lower luminosity limits.

Fig. 2.-- Effective temperature vs. time for stellar models evolving on a transient blue loop caused by sudden, heavy mass loss during the yellow-red phase of dynamical instability in a star of initially 60 $M_\odot$. The luminosity along the blue loop is $\log(L/L_\odot) = 5.91$.



LOG L/L⊙
LOG T_e
6.2
6.0
5.8
5.6
5.4
4.6
4.4
4.2
4.0
3.8
3.6
3.4
α_P=1.4 2.0 2.8
IRC +10420
Var A
HR 5171A
ρCas
HR 8752
V382 Car

Fig. 1

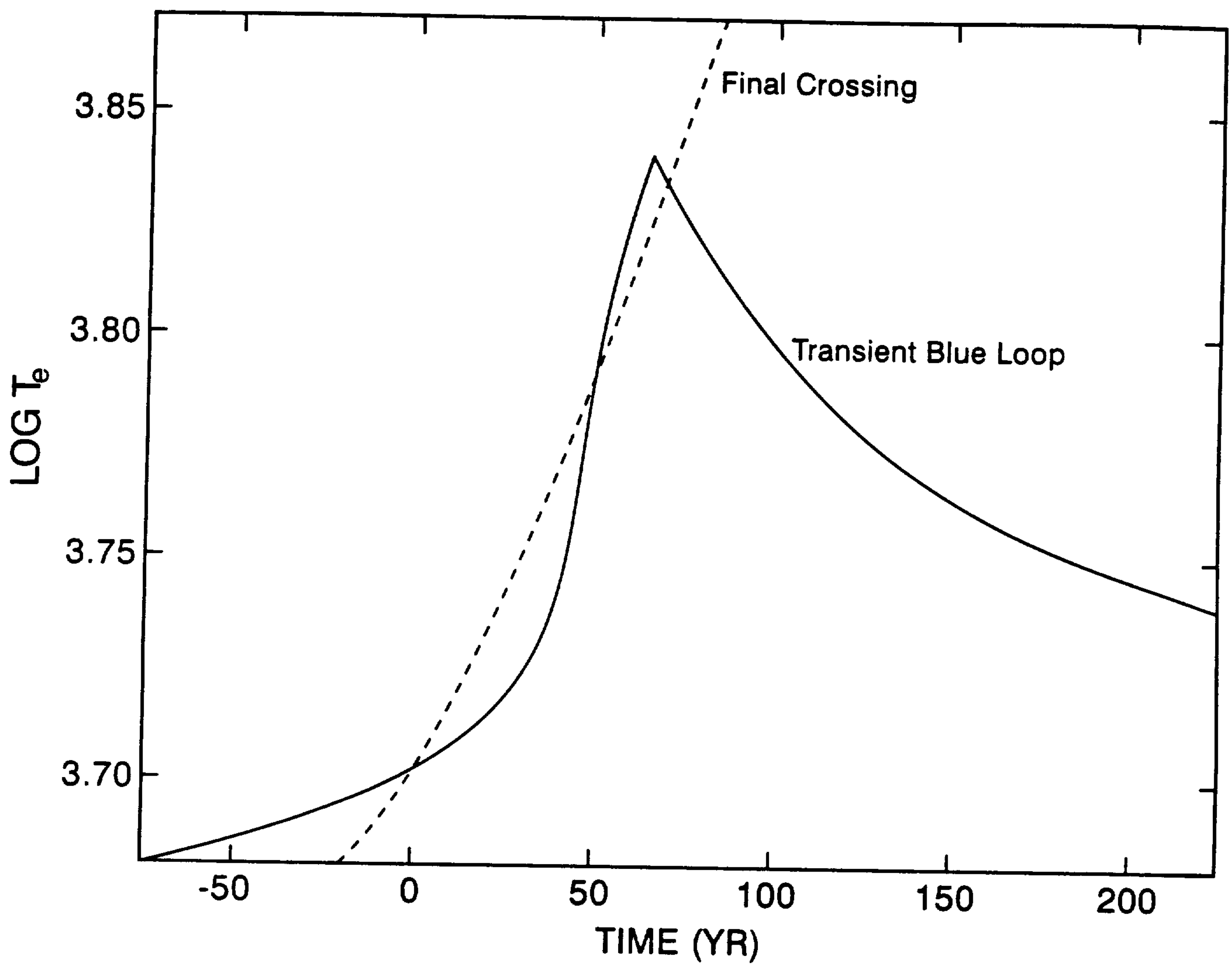

Final Crossing
Transient Blue Loop
3.85
3.80
3.75
3.70
LOG T$_e$
-50
0
50
100
150
200
TIME (YR)

Fig. 2